

Rubberized Asphalt Concrete



Application and Usage



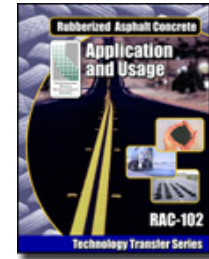
RAC-102

Technology Transfer Series

Application and Usage

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APPLICATION AND USAGE

Scrap tire rubber and other waste rubber products are used to improve the durability and performance of asphalt paving materials. Rubber modification has been shown to provide a number of benefits, including increased resistance to rutting, fatigue and reflective cracking and improved durability, as a function of improved binder properties and increased binder content compared to conventional asphalt concrete mixtures. The fact that rubber modification also provides a long term value-added use of scrap tires should simply be considered as an added benefit.

Rubber modification can be a valuable tool when its use is driven by sound engineering principles and the materials are properly selected and applied for the intended uses. To help in selecting the best approach to solving specific pavement needs in your jurisdiction, this module discusses the types of rubber modification that are available and the appropriate applications of each.

DEFINITIONS

The first step is to define the basic materials and terminology related to rubber modification of asphalt paving materials.

Crumb Rubber Modifier (CRM)

Crumb Rubber Modifier (CRM) is produced from grinding up whole scrap tires from automobiles, trucks, or buses, tread buffings, and other waste rubber products. A variety of processes and equipment are used to produce a wide range of CRM gradations for use as modifiers in asphalt paving materials.



CRM Used for Wet Process

High Natural Rubber (High Natural CRM)

High Natural Rubber (High Natural CRM) is another type of scrap rubber product that includes 40-48 % natural rubber or isoprene and a minimum of 50 % rubber hydrocarbon according to Caltrans and Southern California Greenbook requirements. Sources of high natural rubber include scrap tire rubber from some types of heavy truck tires, but are not limited to scrap tires. Other sources of high natural rubber include scrap from tennis balls and mat rubber.

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Ambient grinding (performed at or above ordinary room temperature) should be used to produce CRM to provide irregularly shaped, torn particles with relatively large surface areas that promote interaction with the paving asphalt. Cryogenic grinding may be used as an intermediate processing step; liquid nitrogen is used to freeze the scrap tire rubber until it becomes brittle and then a hammer mill is used to shatter the frozen rubber. However, this approach yields smooth CRM particles with relatively small surface area that must be subjected to a final grind at ambient temperature in order to be used to modify asphalt binders.

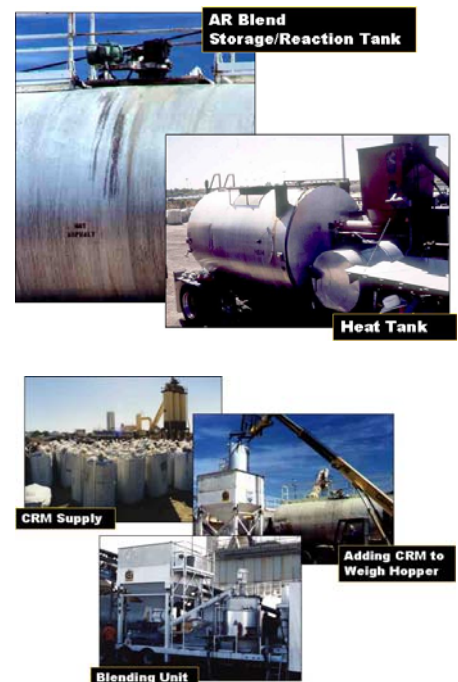
Rubber modification of asphalt concrete mixes is accomplished by two methods: the wet process and the dry process.

Wet Process

This is the most widely used method for modifying asphalt cement with CRM and other components, and is used extensively in Arizona, California, Texas and Florida. The wet process requires thorough mixing of the CRM in hot asphalt cement (typically 400°F to 425°F) and holding the resulting blend at elevated temperatures (325°F to 425°F) for a designated minimum period of time (typically 45 to 60 minutes) to promote an interaction between the CRM and asphalt. Other components such as extender oil (asphalt modifier) and high natural CRM may be included, depending on applicable specifications.

The asphalt-rubber interaction (also referred to as reaction) includes swelling of the CRM particles, a physical exchange of aromatic oils and light fractions between the CRM and the asphalt cement, and development of specified physical properties of the asphalt and CRM blend to meet requirements.

The wet process can be used to produce a wide variety of CRM modified binders that have corresponding ranges of physical properties. However, the most important distinctions among the various blends are related to rotational viscosity of the resulting CRM-asphalt cement blend at high temperature and whether or not the blend requires constant agitation to maintain a relatively uniform distribution of rubber particles. The threshold viscosity is 1,500 cPs or 1.5 Pa-sec at 350°F or 375°F, depending on the governing specification.



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This viscosity threshold distinguishes between the two families of wet process binders, high viscosity and no agitation as defined below. These two families represent very different ranges of physical properties and behavior that should never be considered equivalent or interchangeable, particularly for use in hot mixes. Neither type should be directly substituted for the other. Adjustments in binder content of hot mixes or to spray application rate of surface treatments will be required.

Wet Process-High Viscosity: CRM-modified asphalt binders that maintain or exceed the minimum rotational viscosity threshold of 1,500 cPs or 1.5 Pa-sec at 350°F or 375°F over the interaction period should be described as “wet process–high viscosity” binders to distinguish their physical properties from those of lower viscosity (wet process-no agitation) materials. High viscosity binders require agitation to keep the CRM particles evenly distributed. They may be manufactured in large stationary tanks or in mobile blending units that pump into agitated stationary or mobile storage tanks.

Asphalt-rubber is a type of wet process high viscosity binder used in various types of flexible pavement construction including surface treatments and hot mixes. The ASTM definition of asphalt-rubber is “a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 % by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles” (ASTM D 8-02, Vol. 4.03, “Road and Paving Materials” of the Annual Book of ASTM Standards 2005).

The basis of the ASTM definition is the fact that at least 15% scrap tire rubber by binder weight is typically required to achieve the 1,500 cPs threshold viscosity. Viscosity is strongly related to the size of the scrap tire CRM particles and relative tire rubber content of the CRM-modified blend. CRM gradations used in the wet process are minus No. 8 sieve size or finer.

There is also an ASTM Standard Specification for Asphalt-Rubber Binder, ASTM D 6114-02. The ASTM requirements relate binder properties to climate, and cover the types of high viscosity asphalt-rubber binders specified by Caltrans, the Greenbook, Arizona, and other primary user agencies. Typical specification requirements in California include an operating range for rotational viscosity, softening point, and cone penetration, and a minimum value for resilience at room temperature.



Requirements for components, minimum temperatures for the asphalt cement at CRM addition and for interaction of the asphalt and CRM blend, interaction periods, and resulting physical properties of the blend, vary among agencies that use the wet process. For example, the Greenbook references Type 1 and Type 2 Asphalt Rubber Binder. Type 2 binder includes the same components specified by Caltrans

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(asphalt cement, asphalt modifier (extender oil), and both scrap tire and high natural CRM) but allows more variation in the relative proportions of the two types of CRM. Type 1 Asphalt Rubber Binder includes only asphalt cement and scrap tire CRM, the same composition routinely used for asphalt-rubber binders in Arizona, Texas, and Florida. ASTM D 6114 was written to cover both Type 1 and Type 2 binders. It is interesting to note that these two types of high viscosity wet process binders are based on the two original patents for asphalt –rubber binders that expired years ago.

BINDER DESIGN

High viscosity binders must be properly formulated or proportioned to comply with specifications and provide a quality product. Individual components that comply with specifications may be combined and interacted in proportions that also fully comply, but may yield a binder that is not usable. The interaction between asphalt cement and CRM materials is material-specific and depends on a number of factors, including:

- Asphalt Cement Source and Grade
- Rubber Type
- Rubber Source
- Amount of Rubber
- Gradation of Rubber
- Interaction Time
- Interaction Temperature

Therefore, an appropriate asphalt-rubber binder design must be developed using the designated sources and grades of asphalt, asphalt modifier if used, and CRM materials (scrap tire and, if used, high natural) that will be used for the subject project(s). The binder design should include testing to develop and present a design profile of each specification property value measured from samples taken at intervals over a 24-hour interaction period.

Binder Blend Profile

The profile should include, at a minimum, results after an initial interaction period of 45 minutes, 4 hours later, and simulated over night cool down by reducing oven temperature to 275°F for a period of 14 hours starting at 6 hours after CRM addition to 22 hours after CRM addition. After the cool down, the binder should be reheated to the



Remember that the two families of CRM-modified binders, high viscosity and no agitation, are not interchangeable. Neither type should be directly substituted for the other in a hot mix without laboratory testing to determine appropriate adjustments in binder content and possibly aggregate gradation.

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appropriate temperature for viscosity testing after the 24-hour interaction is completed. Viscosity should also be measured and recorded at 2 and 3 hours after addition of the CRM to identify the expected trends for field production. The design profile must identify the specific component materials (source or supplier and grade) and proportions thereof used in the design. If any of the components are changed, the design profile would no longer apply.

Physical Properties Requirements for Type 1 and Type 2 Asphalt-Rubber Binder						
Test Performed	Minutes of Reaction					45 minutes Specification Limits***
	45	90	240	360	1,440	
Viscosity, Haake at 190°C, Pa.s, (10-3), or cP (*See Note)	2400	2800	2800	2800	2100	1500 – 4000
Resilience at 25°C, % Rebound (ASTM D5329)**	27	--	33	--	23	18 Minimum
Ring & Ball Softening Point, °C (ASTM D36)	59.0	59.5	59.5	60.0	58.5	52 – 74
Cone Pen. at 25°C, 150g, 5 sec., 1/10 mm (ASTM D217)	39	--	46	--	50	25 – 70

Test Parameter	ASTM Test Method	Requirement	
		Min.	Max.
Cone Penetration @ 77°F, 1/10 mm	D 217	25	70
Resilience @ 77°F, Percent rebound	D 5329	18	—
Field Softening Point, °F	D 36	125	165
For Type 1 Binder: Viscosity @ 350°F, Pa-s (x10-3)	See Note	1500	4000
For Type 2 Binder: Viscosity @ 375°F, Pa-s (x10-3)	See Note	1500	4000

NOTE: The viscosity test shall be conducted using a hand held high range analog or digital rotational viscometer such as Rion Model VT-04, Haake Model VT-02 or VT-02 plus with Rotor 1, 24 mm in depth x 53 mm in height, or equivalent. The accuracy of the viscometer shall be verified by comparing the viscosity results obtained with the hand held viscometer to 3 separate calibration fluids of known viscosities ranging from 1000 to 5000 Pa-s (x10-3) or centipoises (cPs). The viscometer will be considered accurate if the values obtained are within 300 Pa-s (x10-3) (300 cPs) of the known viscosity. The known viscosity value shall be based on the fluid manufacturers standard test temperature or the test temperature versus viscosity correlation table provided by the fluid manufacturer. Viscometers used on the project shall be verified to be accurate. The accuracy verification results shall be provided to the Engineer.

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Field Viscosity - Measurement is achieved by a rotational viscometer and presented in centipoise (cP) or Pascal Seconds (Pa-s).

Monitors fluid consistency of asphalt rubber binder to ensure pumpability, to identify binder changes which might affect hot mix placement and compaction. If the Brookfield is the required method for acceptance, then the Haake viscometer should be calibrated and corrected to the Brookfield measurement for field use.

Resilience ASTM D5329

Measures the elastic properties of the asphalt rubber binder and is expressed as a percentage of rebound for the binder. Resilience is one of the most important properties in the specifications and is a more reliable measure of elasticity.

Softening Point ASTM D36 - AASHTO T 53

Measurement is achieved by the ring and ball method and presented in °F or °C and is an indicator of material stiffness. This shows the tendency of the material to flow at elevated temperatures.

Cone Penetration ASTM D 5 - AASHTO T 49

Measurement is achieved by a penetrometer and presented in tenths of a millimeter units. Asphalt rubber binder consistency can be evaluated at low, moderate, and high temperatures. Needle penetration is usually the standard at 39.2°F and 77.0°F. Cone penetration is typically used with asphalt rubber binder with larger particle size crumb rubber (10 mesh and up).

The design profile indicates the compatibility of the components and the quality and stability of the resulting asphalt-rubber binder properties. Viscosity and resilience are the most meaningful indicators of performance and are expected to vary as the asphalt-rubber interaction proceeds. Viscosity should remain above the minimum 1,500 cPs value throughout the interaction and should not manifest drastic drops. There is no maximum value for resilience; high resilience typically indicates that the binder should perform well. It is recommended that submittal of the high viscosity binder design profile should be required for both hot mix and spray applications.

Wet Process-No Agitation: CRM-modified binders that do not require constant agitation to keep discrete rubber particles uniformly distributed in the hot asphalt cement.

The term “**terminal blend**” is often used to describe such materials, which include rubber-modified asphalt materials such as Caltrans MB and Greenbook MAC-10TR. However such binders may be produced in the field or at an asphalt concrete plant as well, so calling them terminal blends may be misleading and is unnecessarily restrictive. The preferred description for this type of binder is therefore “wet process-no agitation”. Such binders are typically modified with CRM particles finer than the 600 µm (No. 30) sieve size that can be

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digested (broken down and melted in) relatively quickly and/or can be kept dispersed by normal circulation within the storage tank rather than by agitation by special augers or paddles.

Specifications for No Agitation Wet Process CRM Modified Binders with Minimum Viscosity Less Than 1.5 Pa-sec, 1500 cPs					
Agency	Greenbook	Caltrans			
Binder Designation	MAC-10TR	MB-4	MB-5	MB-6	MB-7
Original Physical Properties					
CRM by weight of asphalt cement	Min 10%				
Viscosity AASHTO 202, poise @60°C/140°F/ 135°C/275°F	Min 5000/ Max 10				
Needle Penetration @ 25°C/77°F, 100g, 5 sec, 0.1 mm	40-60				
Softening Point, °C/°F, min	53°C/127°F				
Needle Penetration @ 4°C/39.2°F, 200g, 60 sec, 0.1 mm	Min 20				
Shear Susceptibility of δ and Viscosity		SSD $\geq 30(0.6 + SSV)^3$ @ 25°C, CT 381			
Tests on TFOT Residue					
Retained penetration ratio @ 25°C/77°F, % of original	RTFO Min 50%				
$\delta \leq 97-6(\log G^*)$ and $G^*/\sin \delta \geq 4.0 \text{ kPa}$ @ 10 rad/sec, @°C		@ 64°C	@ 64°C	@ 64°C	@70°C
Needle Penetration @ 4°C/39.2°F	Min 14				
Needle Penetration @ 25°C/77°F	20-40				
Dynamic Viscosity 60°C/140°F, Poise	Min 20000				
Kinematic Viscosity 135°C/275°F, cSt	Max 1500				
$S \leq 300 \text{ MPa}$, $m \geq 0.30$, 60 sec, @ °C		@ -8°C	@ -19°C	@ -30°C	@ -8°C
Shear Susceptibility of δ and Viscosity		SSD $\geq -115 \text{ SSV} - 50.6$ @ 25°C, CT381			

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Polymers and other additives may also be included. In the past, rubber contents for such blends have generally been $\leq 10\%$ by mass of asphalt or total binder (which does not satisfy the ASTM definition of asphalt-rubber), but some California products may now include 15% or more CRM. Although such binders may develop a considerable level of rubber modification, rotational viscosity values rarely approach the minimum threshold of 1500 cPs that is necessary to significantly increase binder contents above those of conventional AC mixes without excessive drain-down. No agitation binders are used in Arizona, California, Texas and Florida with various concentrations of CRM, but the performance benefits have not equaled those provided by high viscosity binders.

No agitation binders are often proprietary blends for which some of the components may be classified as trade secrets and thus may not be identified by the respective suppliers. However the supplier should be willing and able to certify how much scrap tire and/or other waste rubber products are included. Design profiles have not typically been required or provided for such binders, as they are considered to be relatively stable during storage. Separation and specification compliance tests can be used to evaluate binder quality and stability over time.

Dry Process is any method that includes scrap tire CRM as a substitute for 1 to 3 % of the aggregate in an asphalt concrete paving mixture, not as part of the asphalt binder. This method thus applies only to production of CRM-modified AC mixtures. A variety of CRM gradations have been used, ranging from coarse rubber (1/4" to + No. 8) to "Ultrafine" minus 180 μm (No. 80) sieve sizes of CRM. Several methods have been established for adding the CRM to the aggregate in hot plant mixing units before the mixture is charged with asphalt binder. Caltrans has a special provision for RUMAC, a generic dry process product that includes an intermediate CRM gradation specification.

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ASPHALT RUBBER HOT MIXES

High viscosity binders have a thick consistency that allows significant increases in binder content (up to 2% by total mix weight) compared to conventional asphalt concrete mixes with similar aggregate gradations while minimizing potential for binder drain down. The high binder content is a primary cause of the documented performance benefits of asphalt-rubber hot mixes. However to capitalize on this feature, the aggregate matrix or skeleton must provide sufficient void space to accommodate the CRM particles and a sufficient quantity of high viscosity binder to modify mix behavior. Hot mixes made with high viscosity binders are relatively low modulus materials compared to conventional dense-graded asphalt concrete (DGAC). They perform based on flexibility and resistance to permanent deformation by elastic recovery rather than stiffness like DGAC.



AR Binder Product

Dense-graded Mixes

Dense-graded mixes are not appropriate for use with high viscosity binders because there is not sufficient void space available. However dense gradations are well suited for use with no agitation binders such as Caltrans MB or Greenbook MACT-10TR, and should provide similar structural capacity to conventional DGAC mixes.



Dense Graded

Gap-Graded Mixes

Gap-graded mixes have proven to be a very effective use of high viscosity asphalt rubber binders. They are reportedly the most widely used asphalt-rubber product in California. Caltrans calls this type of mix "Rubberized Asphalt Concrete Type G (RAC-G)". The Greenbook calls it Asphalt-Rubber Hot Mix (ARHM).



Gap Graded

RAC-G/ARHM mixes provide a durable, flexible pavement surface with increased resistance to reflective cracking, rutting and oxidation, good surface friction characteristics due to the texture provided by the aggregate gradation and often reduced traffic noise. Minimum requirements for 18% voids in mineral aggregates (VMA) provide space to accommodate sufficient high viscosity binder, and minimum binder content requirements range from 7.0 to 7.5% by weight of dry aggregate based on pavement performance experience.

The **RAC-G** acts as a structural layer in the pavement and is most effective at compacted thicknesses ranging from 1.2 inches (30 mm) to 2.4 inches (60 mm) according to recent structural analysis and

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modeling. This supports and corresponds to current practice based on empirical experience and economic considerations.

Appropriate uses for RAC-G include overlays of existing pavements or new construction for a wide range of traffic volumes and loadings. RAC-G can be used in urban areas where there is considerable stop-and-go traffic for which open-graded mixes would not be suitable. Such areas include numerous signalized intersections and driveways. However, RAC-G mixtures are not recommended for parking areas as the surface of these low modulus mixes are likely to scuff when subjected to simultaneous low speed braking and turning movements that are typical in such areas.

RAC-G overlay thickness design may be performed according to current Caltrans or AASHTO procedures. Recent research indicates that RAC-G has a gravel factor similar to DGAC but slightly lower, which indicates similar structural capacity in spite of the relatively low modulus. For purely structural considerations, RAC-G may be considered equivalent to DGAC, which corresponds to experience and practice in Arizona and Texas. Structural models indicate that the RAC is most effective in the upper 2 to 3 inches of the pavement structure and use at lower levels provides no added benefit. Should an increase in structural capacity require more than 2.4 inches of hot mix, an intermediate layer of DGAC would be placed and then covered with a thin RAC overlay.

However, when pavement structure is adequate and overlay thickness design is controlled by resistance to reflective cracking, RAC-G can be placed at approximately one-half of the required DGAC thickness due to superior performance in resisting reflective and fatigue cracking. Caltrans has been successfully using this crack reflection performance equivalency for RAC-G overlay thickness design since 1992. The Caltrans Flexible Pavement Rehabilitation Manual provides details for designing a variety of overlay strategies.

Dry process mixes are typically gap-graded to provide space in the aggregate matrix for the CRM particles. Some open-graded mixes have also been used. The asphalt cement is not considered to be modified by the dry process, although there may be some limited interaction of the CRM with the asphalt cement during mixing in the AC plant, silo storage, hauling, placement and compaction. However, there are indications that some level of interaction may continue after construction is completed, which may have pronounced effects on mix design and subsequent pavement performance. Use of the Hveem mix design method, with its extended curing period, should generally account for most of the long term asphalt absorption by the CRM particles and allow selection of appropriate target asphalt content. If long term aging and absorption are not considered in the mix design

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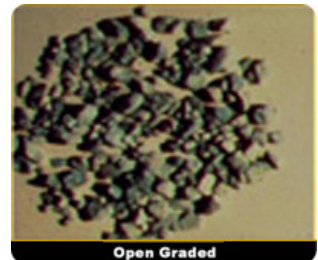
procedure, early raveling of the resulting pavement may occur. Care must also be taken during the mix design to make appropriate adjustments for the low specific gravity of the CRM compared to the aggregate material to assure proper volumetric analysis.

Performance of gap-graded dry process mixes has been mixed, and overall appears to be more variable than performance of wet process mixes. Some dry process mixes have performed well for many years. Failure to account for asphalt absorption by the CRM may have been a contributing factor to a number of early failures of dry process mixes.

Open-Graded Mixes

Open-graded mixes have also proven to be a very effective use of high viscosity asphalt rubber binders, although they have been used more extensively in Arizona than in California. Caltrans has specifications for “Rubberized Asphalt Concrete Type O (RAC-O)”.

The Greenbook has no analog. Open-graded mixes are placed as thin surface layers typically about 1 to 1.2 inches thick. They are not considered structural elements and no thickness reduction is applied for these uses of asphalt rubber. RAC-O and RAC-O-HB provide a durable, highly flexible pavement surface with enhanced drainage and frictional characteristics that reduces splash and hydroplaning in wet conditions. These mixes are also highly resistant to reflection of cracks and joints in PCC pavements, and to reflection of severe cracks from underlying AC pavements.



RAC-O mixes provide good surface frictional characteristics and are intended to be free draining so that surface water can quickly travel through the mat to drain out along the edges of the pavement structure. This reduces splash, spray, and hydroplaning during and immediately after rains and thus improves safety. RAC-O may be considered one of the “new generation” friction course materials that use highly modified binders to address performance and durability issues of conventional open-graded asphalt concrete, but this product has been in use much longer. Asphalt-rubber content is set at 1.2 times the optimum bitumen content for AR-4000 (or PG asphalt) determined according to California Test 368, with a check test for drain off. This content is low for a RAC mix, and the increase over conventional asphalt content simply compensates for the average CRM content of the asphalt-rubber binder.

Another reason that RAC-O mixtures are durable is that these are relatively low modulus materials, with lower stress to strain ratios than stiffer materials like DGAC. They move more in response to the same

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level of loading, and function by flexing and recovering (relaxing, creeping, rebounding, etc.) rather than by being stiff.

Caltrans is evaluating use of higher asphalt-rubber binder contents, 8 to 10 percent by mass of dry aggregate, in some open-graded mixtures. These mixtures are called RAC-O-HB, High Binder and use 1.6 times the optimum asphalt cement binder content. Extensive experience in Arizona has shown that asphalt-rubber binder contents can be increased to 10 percent or more by mass of dry aggregate without excessive drain-off because of the high viscosity of the asphalt-rubber binder. Such rich open-graded mixtures have generally provided excellent performance in a variety of climate zones in Arizona, where they are placed at nominal thickness of ½-inch over asphalt concrete pavements and 1-inch thick over portland cement concrete (PCC) pavements. Although the high binder content mixes are not as free draining as RAC-O, the thicker film coating of the asphalt-rubber binder provides improved resistance to fatigue and reflective cracking, as well as to stripping and oxidative aging. These factors increase the durability of open-graded pavements.

RAC-O and RAC-O-HB have also demonstrated significant tire noise reduction, which prompted implementation of a Quiet Pavements program in the Phoenix Arizona metropolitan area. Noise impacts are currently being studied by Caltrans, Arizona DOT, and the Federal Highway Administration (FHWA).

RAC-O and RAC-O (HB) are appropriate for use as a surface course for overlay or new construction for roadways where traffic flow is essentially uninterrupted by signalization, such as some freeways, rural and secondary highways. These mixes are highly effective as an overlay of PCC and AC pavements in locations where potential for reflective and fatigue cracking is severe, and effectiveness increases with increased binder content. They may also be used as a maintenance blanket to restore surface frictional characteristics and to help preserve the underlying pavement. Both types of mixes provide a smooth quiet ride. Open-graded RAC mixes may be considered as an alternative to a chip seal, because hot mixes are less sensitive to construction operations and essentially eliminate threat of windshield breakage

Open graded mixes should not be used where there is a significant amount of stop and go traffic or turning vehicles, such as city streets or in parking lots, because the porous pavement is susceptible to damage from leaking vehicle fluids and scuffing from simultaneous low speed braking and turning movements.

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ASPHALT RUBBER SPRAY APPLICATIONS

Asphalt rubber spray applications may be used as surface treatments or interlayers. Such applications are usually used for maintenance or rehabilitation of existing pavements, and are very effective at resisting reflective cracking. High viscosity binders seem to provide greater benefits for spray applications than do no agitation binders. The asphalt rubber binder design and materials submittals requirements, including test results that verify compliance with asphalt rubber binder physical property specifications, are typically the same as for hot mixes. However, coarser CRM gradations may be used in binders for spray applications if the distributor nozzles are large enough.



Chip seal application

Chip Seals are a type of surface treatment that Caltrans calls “Stress Absorbing Membrane (SAM)” and the Greenbook calls “Asphalt Rubber Aggregate Membrane (ARAM)”. Asphalt rubber chip seals provide a flexible, waterproof, skid resistant and durable surface that resists oxidation and is highly resistant to reflective cracking. Asphalt rubber chip seals provide the same benefits as conventional chip seals, but also provide the additional advantages of significantly longer service life than conventional chip seals, and superior long-term performance in resisting reflective cracking.

Caltrans uses chip seals for preventative and major maintenance to correct surface deficiencies, seal raveled pavement surfaces, seal off and protect the pavement structure against intrusion of surface water, and to protect the pavement surface from oxidation. Chip seals do not make any structural contribution nor correct ride roughness problems. However, where traffic volumes allow, some agencies use them as an alternate to conventional open-graded mixes to restore surface frictional characteristics. In areas where traffic is heavy or fast, lightweight aggregates may be substituted to minimize windshield breakage by loose chips. The Caltrans Maintenance Manual (Volume 1) includes criteria for use of chip seals and cover aggregate size based on speed limits and average daily traffic.

To construct a chip seal, the hot asphalt rubber binder is sprayed on the roadway surface at a rate determined by the Engineer. Application rate depends on the condition of the pavement surface, but is typically between 0.55 and 0.65 gallons per square yard, which provides a relatively thick membrane. The binder is immediately covered with a layer of hot pre-coated aggregate chips that must be quickly embedded into the binder by rolling before the membrane cools. Multiple chip seals consist of multiple applications of binder and cover

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aggregate, with the coarsest aggregate in the bottom layer and successively finer chips in the subsequent layer(s).

Aggregate application rates can be evaluated in the laboratory prior to the start of construction. The easiest method is to simply lay the aggregate one-stone deep on a measured area, weigh the amount of stone required to cover that area and convert to appropriate units.

Typical rates range from about 28 to 44 pounds per square yard. To verify if application rates for binder and chips are appropriate, also check the embedment of the cover aggregate. Individual chips should be embedded to a depth of about 50-70 percent after seating in the lab or by rollers and traffic in the field.

Excess chip application interferes with embedment and adhesion. Bidding chips on a square yard basis rather than by the ton helps minimize over-application of cover aggregate. Loose stones along the roadway edge after sweeping may indicate excessive chip application and wasted stone, that the asphalt rubber application is too light, or that the binder cooled before embedment and adhesion were achieved. Excess asphalt rubber application can literally submerge or swallow the chips, and results in flushing/bleeding.

Best results are achieved with clean single-sized chips, as stated in the Caltrans Maintenance Technical Advisory Guide (MTAG, October 2003). The standard chip size for Caltrans asphalt rubber seals is nominal 3/8-inch, which may be too small for heavy binder applications. However, Caltrans policy is to use 1/2-inch chips only where ADT is less than 5,000 per lane. Although single-sized chips are most desirable, Caltrans and Greenbook specifications are for graded cover aggregates with up to 15% by weight passing the No. 4 sieve. A maximum of 5% passing the 1/4-inch or No. 4 sieve has been shown to provide a better finished product. Because single-sized chips are not the standard, they may be difficult to obtain.

Pre-coating the aggregate with asphalt cement improves adhesion by removing surface dust and "wetting" the chips.

Any paving grade asphalt can be used for precoating. Caltrans and the Greenbook require that the aggregate chips be delivered to the job site precoated and hot. To further aid chip retention after the chips have been embedded and swept, a fog seal (or flush coat per the Greenbook) of asphalt emulsion (diluted 1:1 with water) is sprayed over the chips at a typical rate of about 0.05 to 0.1 gallon per square yard. A light dusting of sand, about 2 to 4



Rubber tire rollers



Sweeping



Flushcoat

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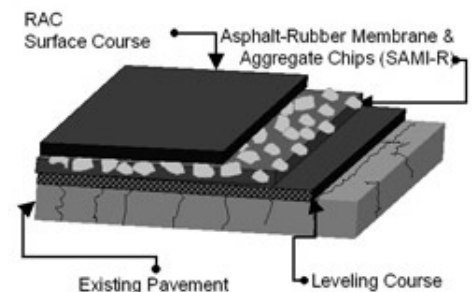
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pounds per square yard, may be applied as a blotter if directed by the Engineer.

Chip seals have been used to restore some serviceability to functionally failed (aged and badly cracked) pavements with relatively sound structural capacity until rehabilitation can be performed. However they are too thin to affect ride, and the aggregate surface may be somewhat noisy and rough to ride on. Appearance may also be an issue, although use of hot precoated chips and flush coat may improve appearance as well as durability. Noise and roughness generated are related to aggregate particle size. Larger cover aggregate is noisier and presents a rougher surface appearance.

Note: All chip seals are very sensitive to construction operations and site environmental conditions. With hot-applied seals, the thin binder membrane cools very quickly regardless of its composition. Embedment and adhesion must be accomplished while the membrane is still hot. Although some references indicate that asphalt-rubber seals can be applied at colder temperatures than emulsion seals due to use of hot precoated chips, it is not advisable to place them when the ambient temperature is less than 60°F. The potential for problems with embedment and adhesion will increase as ambient and surface temperatures decrease.

Asphalt Rubber Interlayers are called Stress Absorbing Membrane Interlayer- Rubber (SAMI-R) or ARAM interlayer. An interlayer is simply an asphalt rubber chip seal that is overlaid with conventional AC or RAC. Interlayers are used under corrective maintenance overlays and as a pavement rehabilitation tool, but would not be included in new construction. The interlayer material is very flexible and elastic and has a low modulus; it flexes and creeps to relieve stresses and to heal many of the cracks that do occur. Interlayers act to interrupt crack propagation and have been shown to be highly effective in minimizing reflective cracking in overlays of existing distressed asphalt and jointed portland cement concrete pavements. The membrane also provides a seal that minimizes further infiltration of surface water through the pavement structure. In cases where reflective cracking is expected to be the primary distress mode and structural capacity is deemed sufficient, interlayers may be used to reduce the required thickness of the overlay.



Asphalt Rubber Interlayers

Interlayers may be applied to any type of rigid (PCC) or asphalt pavement, and have proved very effective at minimizing reflection of PCC joints. However, as the Caltrans Maintenance Manual states, if the surface irregularities (rutting in AC or faulting of PCC) exceed 1/2-

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inch then either a leveling course should be placed or grinding and crack filling are required prior to placing the interlayer.

Chip retention is not an issue unless the interlayer will be opened to traffic prior to overlay. Otherwise, the aggregate chips are sandwiched in. They are keyed into the overlay during compaction and prevent formation of a slippage plane along the relatively thick asphalt rubber membrane. No fog seal or sand should be applied over an interlayer because it could interfere with bonding of the overlay.

Use of chip seals, interlayers, and multiple layer strategies may provide an economic alternative to costly overlays.

Cape Seal is another type of double surface treatment, which consists of an asphalt rubber chip seal covered with slurry seal. Conventional slurry seals are typically used, but rubberized slurry could be substituted. The purpose is the same as for a chip seal, to cover up cracked and aged pavements, minimize further infiltration of surface water, and restore surface friction. The slurry seal surface is quieter than chip seal and provides a smooth, uniform and attractive appearance. Cape seals are most often used on residential streets, or in parking areas for office developments, to enhance appearance of the pavements and reduce noise generated.

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MAINTENANCE

Asphalt rubber materials are used for pavement preservation and maintenance purposes. Caltrans primarily uses thin RAC overlays (possibly over a SAMI-R) as maintenance blankets and also uses single chip seals to restore surface friction. Either gap-or open-graded overlays may be used, depending on traffic, adequacy of the existing pavement structure, and other site conditions.

RAC materials are rarely used for patching unless local plants are manufacturing RAC products for concurrent paving projects. It is too expensive to operate an asphalt-rubber blender unit to make hot mix for routine repairs.

The other aspect is maintenance of asphalt rubber pavements and surface treatments. Typical operations include patching and fog sealing, although the period of time between maintenance treatments is expected to be longer than for conventional DGAC pavements.

RAC materials are not typically available for use in patching as indicated previously. However, if available, RAC-G or ARHM mixes would be appropriate for use in patching other RAC pavements. Open-graded mixes should not be used to construct hot patches, as they will not block infiltration of surface water. If suitable RAC materials are not available, as is usually the case, polymer-modified or conventional DGAC mixes may be used to patch RAC pavements. Good practices for patching conventional DGAC pavements also apply to patching RAC materials and should be followed.

Fog sealing is typically used for preservation and may also be applied to RAC pavements, although frequency of application would be expected to be decreased. RAC mixes that were not adequately compacted may require fog sealing more frequently than expected to protect against moisture and other environmental damage. Fog seal application rates should be governed by the condition of the pavement surface. Rich RAC mixes may only need light fog applications.



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GLOSSARY

Asphalt rubber binder (ARB) – is used in various types of flexible pavement construction including surface treatments and hot mixes. According to the ASTM definition (ASTM D 8, Vol. 4.03, “Road and Paving Materials” of the Annual Book of ASTM Standards 2006) asphalt rubber is “a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles”. By definition, asphalt rubber binder is prepared using the “wet process”. Caltrans specifications for ARB physical properties fall within the ranges listed in ASTM D 6114, “Standard Specification for Asphalt Rubber Binder,” also located in Vol. 4.03. Recycled tire rubber is used for the reclaimed rubber and is currently referred to as crumb rubber modifier (CRM). The asphalt cement and CRM are mixed and interacted at elevated temperatures and under high agitation to promote the physical interaction of the asphalt cement and CRM constituents. During ARB production and storage, agitation is required to keep the CRM particles suspended in the blend. Various petroleum distillates or extender oil may be added to reduce viscosity, facilitate spray applications, and promote workability. (See Wet Process)

Automobile tires – tires with an outside diameter less than 26 inches (660 mm) used on automobiles, pickups, and light trucks.

Crumb rubber modifier (CRM) – general term for scrap tire rubber that is reduced in size for use as modifier in asphalt paving materials. Several types are defined herein. A variety of processes and equipment may be used to accomplish the size reduction as follows:

Types of CRM

Ground crumb rubber modifier – irregularly shaped, torn scrap rubber particles with a large surface area, generally produced by a crackermill.

High natural rubber (Hi Nat) – scrap rubber product that includes 40-48 percent natural rubber or isoprene and a minimum of 50 percent rubber hydrocarbon according to Caltrans requirements. Sources of high natural rubber include scrap tire rubber from some types of heavy truck tires, but are not limited to scrap tires. Other sources of high natural rubber include scrap from tennis balls and mat rubber.

Buffing waste – high quality scrap tire rubber that is a byproduct from the conditioning of tire carcasses in preparation for re-treading. Buffings contain essentially no metal or fiber.

Tread rubber – scrap tire rubber that consists primarily of tread rubber with less than approximately 5 percent sidewall rubber.

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Tread peel – pieces of scrap tire tread rubber that are also a by-product of tire re-treading operations that contain little if any tire cord.

Whole tire rubber – scrap tire rubber that includes tread and sidewalls in proportions that approximate the respective weights in an average tire.

CRM Preparation Methods

Ambient grinding - method of processing where scrap tire rubber is ground or processed at or above ordinary room temperature. Ambient processing is typically required to provide irregularly shaped, torn particles with relatively large surface areas to promote interaction with the asphalt cement.

Cryogenic grinding – process that uses liquid nitrogen to freeze the scrap tire rubber until it becomes brittle and then uses a hammer mill to shatter the frozen rubber into smooth particles with relatively small surface area. This method is used to reduce particle size prior to grinding at ambient temperatures.

Granulation – produces cubical, uniformly shaped, cut crumb rubber particles with a low surface area.

Shredding – process that reduces scrap tires to pieces 6 in.2 (0.023 m²) and smaller prior to granulation or ambient grinding.

CRM Processing Equipment

Cracker mill – apparatus typically used for ambient grinding, that tears apart scrap tire rubber by passing the material between rotating corrugated steel drums, reducing the size of the rubber to a crumb particle generally No. 4 to No. 40 (4.75 mm to 425 mm) sieve size.

Granulator – apparatus that shears apart the scrap tire rubber, cutting the rubber with revolving steel plates that pass at close tolerance, reducing the rubber to cubicle particles generally 3/8 in. to No. 10 sieve (9.5 mm to 2.0 mm) in size.

Micro-mill – process that further grinds crumb rubber particles to sizes below the No. 40 (425 mm) sieve size.

Dense-graded – refers to a continuously graded aggregate blend typically used to make hot-mix asphalt concrete (HMA) pavements with conventional or modified binders.

Devulcanized rubber – rubber that has been subjected to treatment by heat, pressure, or the addition of softening agents after grinding to alter physical and chemical properties of the recycled material.

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Diluent – a lighter petroleum product (typically kerosene or similar product with solvent-like characteristics) added to asphalt rubber binder just before the binder is sprayed on the pavement surface for chip seal applications. The diluent thins the binder to promote fanning and uniform spray application, and then evaporates over time without causing major changes to the asphalt rubber properties. Diluent is not used in ARB to make HMA, and is not recommended for use in interlayers that will be overlaid with HMA in less than 90 days due to on-going evaporation of volatile components.

Dry process – any method that includes scrap tire CRM as a substitute for 1 to 3 % of the aggregate in an asphalt concrete paving mixture, not as part of the asphalt binder. The CRM acts as a rubber aggregate in the paving mixture. This method applies only to production of CRM-modified AC mixtures. A variety of CRM gradations have been used, ranging from coarse rubber (1/4 in. to plus No. 8 (6.3 to 2.36 mm) sieve sizes) to “Ultrafine” minus No. 80 (180 μ m) sized CRM. Caltrans has a special provision for RUMAC which includes an intermediate CRM gradation specification. Care must be taken during the mix design to make appropriate adjustments for the low specific gravity of the CRM compared to the aggregate material to assure proper volumetric analysis. Several methods have been established for feeding the CRM dry with the aggregate into hot plant mixing units before the mixture is charged with asphalt cement. Although there may be some limited interaction of the CRM with the asphalt cement during mixing in the AC plant, silo storage, hauling, placement and compaction, the asphalt cement is not considered to be modified in the dry process.

Extender oil – aromatic oil used to promote the reaction of the asphalt cement and the crumb rubber modifier.

Flush coat – application of diluted emulsified asphalt onto a pavement surface to extend pavement life that may also be used to prevent rock loss in chip seals or raveling in HMA.

Gap-graded – aggregate that is not continuously graded for all size fractions, but is typically missing or low on some of the finer size fractions (minus No. 8 (2.36 mm) or finer). Such gradations typically plot below the maximum density line on a 0.45 power gradation chart. Gap grading is used to promote stone-to-stone contact in HMA and is similar to the gradations used in stone matrix asphalt (SMA), but with relatively low percentages passing the No. 200 (75 μ m) sieve size. This type of gradation is most frequently used to make rubberized asphalt concrete-gap graded (RAC-G) paving mixtures.

Interaction – the physical exchange between asphalt cement and CRM when blended together at elevated temperatures which includes swelling of the rubber particles and development of specified physical properties of the asphalt and CRM blend to meet requirements. Although often referred to as reaction, interaction is not a chemical reaction but rather a physical interaction in which the CRM absorbs aromatic oils and light fractions (small volatile or active molecules) from the asphalt cement, and releases some of the similar oils used in rubber compounding into the asphalt cement. The interaction may be more appropriately defined as polymer swell.

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Lightweight aggregate – porous aggregate with very low density such as expanded shale, which is typically manufactured. It has been used in chip seals to reduce windshield damage.

Open-graded – aggregate gradation that is intended to be free draining and consists mostly of 2 or 3 nominal sizes of aggregate particles with few fines and 0 to 4 percent by mass passing the No. 200 (0.075 mm) sieve. Open grading is used in hot-mix applications to provide relatively thin surface or wearing courses with good frictional characteristics that quickly drain surface water to reduce hydroplaning, splash and spray.

Reaction – commonly used term for the interaction between asphalt cement and crumb rubber modifier when blended together at elevated temperatures (see Interaction).

Recycled tire rubber – rubber obtained by processing used automobile, truck, or bus tires (essentially highway or “over the road” tires). Chemical requirements for scrap tire rubber are intended to eliminate unsuitable sources of scrap tire rubber such as solid tires; tires from forklifts, aircraft, and earthmoving equipment; and other non-automotive tires that do not provide the appropriate components for asphalt rubber interaction. Non-tire rubber sources may be used only to provide High Natural Rubber to supplement the recycled tire rubber.

Rubberized asphalt - asphalt cement modified with CRM that may include less than 15 percent CRM by mass and thus may not comply with the ASTM definition of asphalt rubber (ASTM D 8, Vol. 4.03). In the past, terminal blends (wet process, no agitation CRM-modified asphalt binders including Modified Binder (MB) materials) have typically fallen in this category.

Rubberized asphalt concrete (RAC) – material produced for hot mix applications by mixing asphalt rubber or rubberized asphalt binder with graded aggregate. RAC may be dense-, gap-, or open-graded.

RUMAC – generic type of dry process RAC mixture that has taken the place of proprietary dry process systems such as PlusRide.

Stress-absorbing membrane (SAM) – a chip seal that consists of a hot asphalt rubber binder sprayed on the existing pavement surface followed immediately by an application of a uniform sized cover aggregate which is then rolled and embedded into the binder membrane. Its nominal thickness generally ranges between 3/8 and 1/2-inch (9 and 12 mm) depending on the size of the cover aggregate. A SAM is a surface treatment that is used primarily to restore surface frictional characteristics, seal cracks and provide a waterproof membrane to minimize the intrusion of surface water into the pavement structure. SAMs are used for pavement preservation, maintenance, and limited repairs. Asphalt rubber SAMs minimize reflective cracking from an underlying distressed asphalt or rigid pavement, and can help maintain serviceability of the pavement pending rehabilitation or reconstruction operations.

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Stress-absorbing membrane interlayer (SAMI) - originally defined as a spray application of asphalt rubber binder and cover aggregate. However, interlayers now may include asphalt rubber chip seal (SAMI-R), fabric (SAMI-F), or fine unbound aggregate.

Stress-absorbing membrane interlayer-Rubber (SAMI-R) – SAMI-R is an asphalt rubber SAM that is overlaid with an asphalt paving mix that may or may not include CRM. The SAMI-R delays the propagation of the cracks (reflective cracking) through the new overlay.

Terminal blend – See Wet Process – No Agitation

Truck tires – tires with an outside diameter greater than 26 inches (660 mm) and less than 60 inches (1520 mm); used on commercial trucks and buses.

Viscosity – is the property of resistance to flow (shearing force) in a fluid or semi-fluid. Thick stiff fluids such as asphalt rubber have high viscosity; water has low viscosity. Viscosity is specified as a measure of field quality control for asphalt rubber production and its use in RAC mixtures.

Vulcanized rubber – crude or synthetic rubber that has been subjected to treatment by chemicals, heat and/or pressure to improve strength, stability, durability, etc. Tire rubber is vulcanized.

Wet Process - the method of modifying asphalt binder with CRM produced from scrap tire rubber and other components as required before incorporating the binder into the asphalt paving materials. Caltrans requires the use of extender oil and addition of high natural CRM. The wet process requires thorough mixing of the crumb CRM in hot asphalt cement (375°F to 435°F, 190°C to 224°C) and holding the resulting blend at elevated temperatures (375°F to 425°F, 190°C to 218°C) for a designated minimum period of time (typically 45 minutes) to permit an interaction between the CRM and asphalt. Caltrans specification requirements include an operating range for rotational viscosity and cone penetration, and minimum values of softening point and resilience.

The wet process can be used to produce a wide variety of CRM modified binders that have corresponding respective ranges of physical properties. However the most important distinctions among the various blends seem to be related to rotational viscosity of the resulting CRM-asphalt cement blend at high temperature (threshold is 1,500 centipoises (cPs) or 1.5 Pa/sec at 375°F (190°C) depending on governing specification) and whether or not the blend requires constant agitation to maintain a relatively uniform distribution of rubber particles. Viscosity is strongly related to the size of the scrap tire CRM particles and tire rubber content of the CRM-modified blend. CRM gradations used in the wet process are typically minus No. 10 (2 mm) sieve size or finer. CRM-modified binders with viscosities = 1,500 cPs at 375°F (190°C) should be assumed to require agitation.

Wet Process-No Agitation - a form of the wet process where CRM is blended with hot asphalt cement at the refinery or at an asphalt storage and distribution terminal and transported to the HMA mixing plant or job site for use. This type of rubberized asphalt (which includes Rubber Modified Binder, RMB) does not require subsequent agitation to

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keep the CRM particles evenly dispersed in the modified binder. The term “terminal blend” is often used to describe such materials, although they may also be produced in the field. Therefore, calling them terminal blends is unnecessarily restrictive and the preferred description for this type of binder is “wet process-no agitation”. Such binders are typically modified with CRM particles finer than the No. 50 (300 μm) sieve size that can be digested (broken down and melted in) relatively quickly and/or can be kept dispersed by normal circulation within the storage tank rather than by agitation by special augers or paddles. Polymers and other additives may also be included. In the past, rubber contents for such blends have generally been = 10% by mass of asphalt or total binder (which does not satisfy the ASTM D 8 definition of asphalt rubber), but current reports indicate some California products now include 15% or more CRM. Although such binders may develop a considerable level of rubber modification, rotational viscosity values rarely approach the minimum threshold of 1500 (cPs) or 1.5 Pa/s at 375°F (190°C), that is necessary to significantly increase binder contents above those of conventional HMA mixes without excessive drain-down.

Wet Process-High Viscosity - CRM-modified binders that maintain or exceed the minimum rotational viscosity threshold of 1500 cPs at 375°F (190°C) over the interaction period should be described as “wet process–high viscosity” binders to distinguish their physical properties from those of wet process–no agitation materials. These binders require agitation to keep the CRM particles evenly distributed. They may be manufactured in large stationary tanks or in mobile blending units that pump into agitated stationary or mobile storage tanks. Wet process-high viscosity binders include asphalt rubber materials that meet the requirements of ASTM D6114. Wet process-high viscosity binders typically require at least 15% scrap tire rubber to achieve the threshold viscosity. Caltrans requires a minimum total CRM content of 18%.

Aggregates for Asphalt Concrete

Classification of Rock

- Sedimentary
- Igneous
- Metamorphic

Aggregate Sources

- Natural aggregates - gravel, sand
- Processed aggregates - crushed aggregate
- Synthetic aggregates - blast furnace slag

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Maximum Particle Size and Gradation

- Specified for each asphalt concrete paving mix
- Coarse aggregate - retained on the No. 4 sieve
- Fine aggregate - passes the No. 4 sieve
- Mineral filler/dust - passes the No. 200 sieve

Specific Gravity

- Aggregates of low specific gravity cover a larger volume per ton and, therefore, require a higher percentage of asphalt cement.
- Aggregates of high specific gravity cover a lower volume per ton and, therefore, require a lower percentage of asphalt cement.

Cleanliness

- Free of unsuitable material
- Toughness
- Abrasion resistant

Particle Shape

- Crushed particles interlock to provide strength.
- Fine, rounded particles provide workability but act as ball bearings in the mix so content should be limited. Many agencies limit such materials to a maximum of 15% of the total aggregate to minimize adverse effects on aggregate interlock and VMA.

Surface Texture

- Asphalt tends to strip from smooth surfaces.

Absorptive Capacity

- Ability to absorb asphalt influences the total amount of asphalt required. High absorption increases binder content.

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Affinity to Asphalt

- Ability of the aggregate to bond with the asphalt binder

Asphalt

Characteristics

- Black cementitious material made up largely of hydrocarbons
- A visco-elastic plastic material - brittle and hard when cold; soft and viscous when hot

Classifications

- Asphalt cement (paving grade asphalt)
- Liquid asphalt (mixed with cutbacks) - not used in RAC
- Emulsified asphalt (mixed with water) - not used in RAC

Physical Properties

- Durability
- Adhesion
- Temperature susceptibility - CRM modification reduces temperature susceptibility
- Aging and hardening

Testing of Asphalts

The following tests are used for asphalt rubber binders, but not for testing Performance Graded (PG) asphalt

Viscosity - ability to flow, consistency - temperature dependent

Penetration - hardness value, also measure of consistency at single temperature

Flashpoint - temperature at which a sample "flashes" i.e. bursts into flame

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Thin Film Test/Rolling Thin Film Test - aging methods

Ductility – discrete CRM particles affect test results, typically exhibits early fracture.

Stability – limited to emulsions. For no agitation binders, use separation test and specification compliance testing to evaluate stability of properties

Specific Gravity – used in volumetric mix design calculations, and for metering during mix production

Mix Design Methods

- Marshall Mix Design Method
- Hot mix asphalt paving mixes, one-inch maximum size aggregate (for 4-inch molds)
- Determines optimum asphalt cement content for a particular blend of aggregates.
- Principal features are: 1) a density/void analysis and 2) a Marshall stability/ flow test.

HVEEM Mix Design Method

- Hot mix paving, one-inch maximum size aggregate
- Principal features are:
- Centrifuge Kerosene Equivalent
- Hveem Stability test
- Swell test (permeability)
- Air voids
- Bleeding/flushing.

Mix Design Characteristics

- Mix design of asphalt and rubberized asphalt paving mixes is a trade-off between high binder content to enhance long term durability and performance, and sufficient in-place void space to avoid rutting, instability, flushing and bleeding.
- Air voids provide spaces for the movement of the asphalt cement or asphalt rubber binder within the compacted mix.
- High air voids indicate relatively low density and increased permeability of the compacted mix. The maximum design target is 6% air voids, for special high volume and/or hot climate conditions.
- Low density typically results in raveling and/or stripping, increased susceptibility to aging, fatigue, and environmental damage, and related reduced service life.
- Low air voids indicate relatively high density and increased tendency for asphalt flushing, and mixture rutting and shoving. The minimum design target is 3% air voids.

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- High density also enhances resistance to fatigue and environmental damage, long term performance and durability, as long as in-place air voids are sufficient to prevent bleeding or instability.

Voids in Mineral Aggregate (VMA)

- Total voids excluding those permeable to water and asphalt. VMA is a function of aggregate gradation, particle shape and texture.
- Proper VMA provides sufficient space for binder, which results in durable asphalt film thickness.

Design Asphalt Content

- Depends on aggregate gradation (particularly VMA), ability to absorb asphalt, and compaction type and effort. Hveem and Marshall Methods will yield different results for the same mixture.
- Mineral filler greatly affects design asphalt binder content. Too much filler fills the voids, reduces VMA, and has high demand for binder which results in a dry mix. Too little filler results in a wet mix. However very little filler is used in RAC mixes due to limitations on percentage passing the No. 200 sieve size.

Mix Design Properties

Stability

- Ability to resist shoving and rutting, i.e. permanent deformation.
- Dependent on internal friction of the aggregates (interlock) and the cohesion of the asphalt binder to the aggregate surface.
- Angular aggregate particles with a rough surface texture result in pavements with high stability.

Durability

- Ability to resist changes in the asphalt (polymerization and oxidation), aggregate disintegration, and stripping of the asphalt film
- Durability can be enhanced by increasing the asphalt binder, and achieving proper compaction

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Impermeability

- Related to the air void content and the characteristics of the voids (whether they are interconnected, the size of voids, and whether the voids are at the surface). The size of the voids is related to the sizes of the aggregate particles; large stone mixes have larger individual voids.

Workability

- Workability describes the ease with which the mix can be placed and compacted.
- Harsh mixes (coarse aggregates, few fines) tend to have low workability - RAC-G mixes are not amenable to handwork
- Tender mixes (too much sand or rounded aggregate particles) tend to shove during rolling.
- Temperature of the mix greatly affects workability.

Flexibility

- Ability to adjust to gradual changes in the subgrade or unequal stresses in overlays across cracks without cracking.
- Open or gap-graded mixes have more flexibility than dense-graded mixes because of higher asphalt rubber binder content and, therefore, are used when resistance to reflective cracking is desired.

Fatigue Resistance

- Ability to resist repeated bending and deflection under wheel loads
- Low air void content and high asphalt content increase fatigue resistance.
- High viscosity asphalt-rubber binders have been shown to be highly resistant to fatigue cracking

Skid Resistance

- Measures the ability of the asphalt surface to resist skidding or slipping of vehicle tires. Rough pavement has higher skid resistance than smooth or flushed pavements.

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Typical Asphalt Paving Failures

Edge Failure

- Insufficient thickness, lack of lateral support, base saturated or heavy wheel loads

Weathered or Dry Surface

- Insufficient binder content during mix production, loss of binder due to stripping or raveling, overheating, or absorptive aggregates

Pot Holes

- Structural failure due to lack of base and/or subgrade support, insufficient pavement thickness, or segregated mix. Water infiltration is generally an important contributing factor.

Alligator (Fatigue) Cracking

- Structural failure due to lack of base and/or subgrade support, insufficient pavement thickness, insufficient or aged binder, or water saturation

Bleeding and Instability

- Excessive binder content, heavy tack coat, excessive aggregate fines, rounded aggregates, low air void content

Raveling

- Lean (low binder content) or overheated mix
- Low density/under compacted

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Slipping

- High shear stresses, lack of bond with underlying layer due to improper tack coating or inadequate cleaning of existing surface

Stripping

- Loss of binder, most often due to moisture damage or aggregate surface characteristics.

Surface Erosion

- Water running or standing on pavement for long periods of time
- Soft aggregates

Longitudinal or Transverse Cracking

- Reflective cracks from existing pavement - difficult to prevent. Resistance to reflective cracking is one of the primary performance benefits of asphalt-rubber hot mixes.
- Longitudinal cracking usually manifests along paving joints; if located in the wheel paths, it is a precursor to alligator cracking